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## A FOUR-FLUID MODEL OF PWR DEGRADED CORES\*

by

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### 1. INTRODUCTION

This paper describes the new two-dimensional, four-fluid fluid dynamics and heat transfer (FLUIDS) module of the MELPROG[1] code. MELPROG is designed to give an integrated, mechanistic treatment of pressurized water reactor (PWR) core meltdown accidents from accident initiation to vessel melt-through. The code has a modular data storage and transfer structure, with each module providing the others with boundary conditions at each computational time step. Thus the FLUIDS module receives mass and energy source terms from the fuel pin module, the structures module, and the debris bed module, and radiation energy source terms from the radiation module. MELPROG, which models the reactor vessel, is also designed to model the vessel as a component in the TRAC/PF1[2] networking solution of a PWR reactor coolant system (RCS). The coupling between TRAC and MELPROG is implicit in the fluid dynamics of the reactor coolant (liquid water and steam), allowing an accurate simulation of the coupling between the vessel and the rest of the RCS during an accident. This paper will deal specifically with the numerical model of fluid dynamics and heat transfer within the reactor vessel, which allows a much more realistic simulation (with less restrictive assumptions on physical behavior) of the accident than has been possible before.

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## 2. PHYSICAL BASIS FOR THE MODEL

The progression of an accident sequence in a commercial PWR through core meltdown involves the discrete motion of at least four different classes of materials. First, the motion of liquid water through the core determines the amount of heat removed and the rate of progression of the initial stages of the accident. Second, steam generated by boiling in the core tends to separate from the liquid, accumulating in the higher regions of the primary system. The relative distribution of steam and liquid water in the core is critical to determining core coolability. Third, oxidized and embrittled fuel pins can shatter, forming packed debris beds supported by the lower core support structure. And fourth, fuel pins, structure and debris beds can melt, redistributing material to the lower plenum. Gravity will always tend to separate these four material classes. A truly mechanistic model (one that does not rely on assumptions of gross phenomenology) must track the distribution, velocity and temperature of each of these material classes separately. This is done here by treating each of the four classes with continuum mechanics, and so is termed a "four-fluid" model.

These four fluids must also be tracked in at least two dimensions. Heat generation tends to be greater near the center (radially) of the vessel, while heat loss to structures tends to be greater near the edge. Initial core deformation will tend to occur near the center, which will decrease convective energy removal near the center and increase it further out. Mass (most importantly, fission products) and energy transport by natural convection cells which couple the core to the upper plenum and possibly upper head may be crucial to determining the outcome of an accident sequence. A two-dimensional model is clearly necessary to simulate these phenomena. A three-dimensional model, which could also properly locate the hot and cold leg nozzles (these locations are

asymmetrical in two dimensions), would be preferable, but the added expense and complication the extra dimension would entail are not considered justified presently.

The purpose of the fluids module of MELPROG, then, is to predict the distribution, velocity and temperature of the four material classes or "fluids" described above in a two-dimensional representation of a PWR vessel during an accident sequence. The model relies heavily on the TRAC code development effort, both for basic numerical methods and for actual coding that calculates equation of state and exchange terms for liquid water and steam.

### 3. BASIC EQUATIONS

The problem described above requires the simultaneous solution of the conservation equations of mass, axial momentum, radial momentum, and energy for each of the four fluids. The gas is modeled as a mixture of steam and hydrogen, so an additional hydrogen mass conservation equation is required. The four fluids are identified in the following equations by the index  $f$ , which is defined in Table I.

The differential forms of the equations will be listed and discussed. The finite difference forms will be given as part of the description of the solution algorithm that follows. The mass conservation equations have the following form for fluid  $f$ :

$$\frac{\partial}{\partial t} (\alpha_f \rho_f) + \nabla \cdot (\alpha_f \rho_f \vec{V}_f) - \sum_{k=1}^4 \Gamma_{kf} - \Gamma_f = 0. \quad (1)$$

$\alpha_f$  is the volume fraction of fluid  $f$  with respect to the total geometric cell volume (not flow volume). The non-flow volume fraction in the cell (made

TABLE 1

Fluid Number (f)	Material
1	gas mixture of steam and hydrogen
2	liquid water
3	solid corium
4	molten corium

up of fuel pins and other vessel structural material) is designated  $\alpha_s$ . This formulation is required because  $\alpha_s$  can change with time as core structures deform and fall to lower regions of the vessel. This movement of structural material is accomplished by transferring the structure mass and energy into the third or fourth fluid, depending on whether it is molten or not.

The third and fourth terms represent mass transfer among the fluids and external mass source terms, respectively. The mass transfer between steam and liquid water is treated implicitly in temperature and pressure, while the other mass transfers are treated explicitly.

The hydrogen mass conservation equation is

$$\frac{\partial}{\partial t} (\alpha_1 \rho_h) + \nabla \cdot (\alpha_1 \rho_h \vec{V}_1) - \Gamma_h = 0 . \quad (2)$$

The external mass source term  $\Gamma_h$  is produced by burning of the Zircalloy fuel pin cladding.

The axial momentum equations have the following form for fluid f

$$\begin{aligned} & \frac{\partial}{\partial t} VZ_f + \vec{V}_f \cdot \nabla VZ_f + \frac{1}{\rho_f} \frac{\partial P}{\partial Z} \\ & + \frac{1}{(\alpha\rho)_f} \sum_{k=1}^4 CFZ_{kf} (VZ_f - VZ_k)(VZ_f - VZ_k) \\ & + \frac{1}{(\alpha\rho)_f} (CWZ_f - VZ_f)(VZ_f) + g = 0 . \end{aligned} \quad (3)$$

The fourth term represents momentum transfer among the fluids, while the fifth term represents wall friction. Coefficients CFZ and CWZ are evaluated explicitly on the basis of local flow regime. The radial momentum equations are

completely analogous to equations (3), with the exception of gravitational acceleration

$$\begin{aligned} & \frac{\partial}{\partial t} \mathbf{v}_{Rf} + \vec{\mathbf{v}}_f \cdot \nabla \mathbf{v}_{Rf} + \frac{1}{\rho_f} \frac{\partial p}{\partial \mathbf{R}} \\ & + \frac{1}{(\alpha \rho)_f} \sum_{k=1}^4 C_{kf} (\mathbf{v}_{Rf} - \mathbf{v}_{Rk}) |\mathbf{v}_{Rf} - \mathbf{v}_{Rk}| + \frac{1}{(\alpha \rho)_f} (\mathbf{v}_{Rf} \cdot \mathbf{v}_{Rf}) |\mathbf{v}_{Rf}| = 0 . \end{aligned} \quad (4)$$

The energy equations are given by

$$\begin{aligned} & \frac{\partial}{\partial t} (\alpha_f \rho_f u_f) + \nabla \cdot (\alpha_f \rho_f u_f \vec{\mathbf{v}}_f) + p \left( \frac{\partial \alpha_f}{\partial t} + \nabla \cdot \alpha_f \vec{\mathbf{v}}_f \right) \\ & - \sum_{k=1}^4 \Gamma_{kf} h_{sf} - \sum_{k=1}^4 Q_{kf} - Q_f = 0 . \end{aligned} \quad (5)$$

The third term is the work term. The fourth term represents energy exchange between the fluids due to phase change with  $h_{sf}$  representing the saturation enthalpy of fluid  $f$ . The fifth term represents heat transfer between the fluids. The sixth term represents external energy sources provided by other modules of MELPROG.

Finally, a constraint on the sum of the fluid volume fractions is required:

$$1 - \sum_{f=1}^4 \alpha_f - \alpha_s = 0 . \quad (6)$$

Equations (1) through (5) are a set of seventeen coupled, non-linear, partial differential equations that, along with material equations of state and relations for mass, energy and momentum exchange, provide the basis for a solution of the problem. The description of the solution algorithm that follows

assumes that all four fluids are in fact present throughout the reactor vessel. Fortunately this is rarely true, so that a significant reduction in the complexity of the problem is usually possible. The steps taken to<sup>-1</sup> maximize this reduction in complexity will be described later.

#### 4 . SOLUTION ALGORITHM

The algorithm used to solve this equation set is based on the Stability Enhancing Two-Step (SETS)[3] method, which is used to solve the one-dimensional, two-fluid problem in TRAC/PE1. SETS has enhanced numerical stability characteristics that allow the material Courant condition to be exceeded under some conditions, resulting in longer computational time steps and a less expensive calculation. Compared to the usual semi-implicit method (for example, as used in the TRAC/PE1 three-dimensional vessel component), SETS also has enhanced stability characteristics for problems with phase change, because of a more implicit treatment of momentum coupling between the fluids and of the partition of volume fraction within a cell. The algorithm was developed partly from the previous one-dimensional, three-fluid FLUIDS module of MIMAS[4], which also utilized SETS. The algorithm consists of three main parts - the momentum equation solver, the basic step, and the mass and energy stabilizers. These parts are described in detail, followed by a discussion of the treatment of low volume fractions.

##### A. Momentum Equations

The usual fluid-dynamics staggered grid[5] is used for the spacial finite-differencing of the differential equations. In this scheme, pressures, volume fractions, and fluid state variables are evaluated using cell-centered (i,j) control volumes, while velocities are evaluated using cell-edge centered control volumes. Thus all the terms in the axial momentum equations (3) are

evaluated using control volumes centered at  $(i, j+1/2)$  and all the terms in the radial momentum equations (4) using control volumes centered at  $(i+1/2, j)$ .

Terms in equations (3) requiring further finite difference expansion are the following:

$$(\vec{V} \cdot \nabla VZ)_{i, j+1/2} = \frac{VZ_{i, j+1/2} [VZ]_Z}{\frac{1}{2}(\Delta Z_j + \Delta Z_{j+1})} + \frac{VR_{i, j+1/2} [VZ]_R}{\frac{1}{2}(\Delta R_i + \Delta R_{i+1})} \quad (7)$$

$$\begin{aligned} \text{where } [VZ]_Z &= VZ_{i, j+1/2} - VZ_{i, j-1/2} \quad \text{if } VZ_{i, j+1/2} \geq 0 \\ &= VZ_{i, j+1/2} - VZ_{i, j+3/2} \quad \text{if } VZ_{i, j+1/2} < 0 \end{aligned} \quad (8)$$

$$\begin{aligned} \text{and } [VZ]_R &= VZ_{i-1/2, j+1/2} - VZ_{i+1/2, j+1/2} \quad \text{if } VR_{i, j+1/2} \geq 0 \\ &= VZ_{i+1/2, j+1/2} - VZ_{i-1/2, j+1/2} \quad \text{if } VR_{i, j+1/2} < 0 \end{aligned} \quad (9)$$

$$\text{where } VR_{i, j+1/2} = \frac{(VR_{i+1/2, j} + VR_{i+1/2, j+1} + VR_{i-1/2, j} + VR_{i-1/2, j+1})}{4} \quad (10)$$

$$\left(\frac{1}{\rho_r} \frac{\partial p}{\partial Z}\right)_{i, j+1/2} = \frac{1}{\frac{1}{2}(\rho_{i, j} + \rho_{i, j+1})} \frac{(p_{i, j+1} - p_{i, j})}{\frac{1}{2}(\Delta Z_j + \Delta Z_{j+1})} \quad (11)$$

$$\frac{1}{(\alpha\rho)_{i,j+\frac{1}{2}}} = \frac{2}{[(\alpha\rho)_{i,j} + (\alpha\rho)_{i,j+1}]} \quad (12)$$

Analogous expressions are used for terms in the radial momentum equations (4). These spacial finite difference forms will not be repeated so that the following equations can clearly show the different temporal differencing and linearization schemes.

The goal in this step is to reduce equations (3) and (4) into simple linear relationships between each local fluid velocity and an associated pressure gradient. This can be done easily by evaluating all the terms except the non-steady term using old-time level velocities, but this fully explicit technique has limited stability characteristics. A fully implicit, iterative solution is also possible, but very expensive. SETS provides an intermediate method, in which successive linearizations provide separate implicit solutions for the major couplings - among the fluid velocities in each cell and convectively between cells for each fluid.

The solution procedure for the axial momentum equations will be discussed, with an analogous procedure used for the radial momentum equations. In the first linearization old-time level velocities are used in the convective terms, decoupling the equations spatially.

$$\begin{aligned} & \frac{VZp_f^{n+1} - VZp_f^n}{\Delta t} + \vec{v}_f^n \cdot \nabla VZS_f^n + \frac{1}{\rho_f^n} \frac{\partial p^n}{\partial Z} \\ & + \frac{1}{(\alpha\rho)_f^n} \sum_{k=1}^4 (TZ_{kf} \{2(VZp_f^{n+1} - VZp_k^{n+1}) - (VZ_f^n - VZ_k^n)\} (VZ_f^n - VZ_k^n)) \end{aligned}$$

$$+ \frac{1}{(\alpha\rho)_f^n} \text{CWZ}_f (2\text{VZP}_f^{n+1} - \text{VZ}_f^n) \text{VZ}_f^n + g = 0. \quad (13)$$

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Equations (13) represent a 4x4 system of equations in  $\text{VZP}^{n+1}$  at each mesh cell, which are solved directly. These velocities are called predictor velocities, and represent the effect of coupling between the fluids within each cell. The third and fourth terms in (13) represent temporal expansions of the analogous terms in (3) (see Ref. 3). The second linearization uses the predictor velocities for the intra-cell fluid interaction terms (decoupling the fluid equations from each other), while solving for the convective terms.

$$\begin{aligned} & \frac{\text{VZS}_f^{n+1} - \text{VZ}_f^n}{\Delta t} + \vec{\text{V}}_f^n \cdot \nabla \text{VZS}_f^{n+1} + \frac{1}{\rho_f^n} \frac{\partial p^n}{\partial Z} \\ & + \frac{1}{(\alpha\rho)_f^n} \sum_{k=1}^4 \text{CFZ}_{kf} \{2(\text{VZP}_f^{n+1} - \text{VZP}_k^{n+1}) - (\text{VZ}_f^n - \text{VZ}_k^n)\} (\text{VZ}_f^n - \text{VZ}_k^n) \\ & + \frac{1}{(\alpha\rho)_f^n} \text{CWZ}_f (2\text{VZP}_f^{n+1} - \text{VZ}_f^n) \text{VZ}_f^n + g = 0. \end{aligned} \quad (14)$$

Equations (14) represent four uncoupled systems of equations in  $\text{VZS}^{n+1}$ , which are solved iteratively. These velocities are called stabilizer velocities, and represent the effects of coupling between cells. The third linearization uses stabilizer velocities for the convective terms, with new time-level pressures.

$$\begin{aligned}
 & \frac{vZ_f^{n+1} - vZ_f^n}{\Delta t} + \vec{v}_f^n \cdot \nabla vZS_f^{n+1} + \frac{1}{\rho_f^n} \frac{\partial p^{n+1}}{\partial z} \\
 & + \frac{1}{(\alpha\rho)_f^n} \sum_{k=1}^4 CFZ_{kf} \{2(vZ_f^{n+1} - vZ_k^{n+1}) - (vZ_f^n - vZ_k^n)\} (vZ_f^n - vZ_k^n) \\
 & + \frac{1}{(\alpha\rho)_f^n} CWZ_f (2vZ_f^{n+1} - vZ_f^n) (vZ_f^n) + g = 0
 \end{aligned} \tag{15}$$

Equations (15) also represents a 4x4 system in velocities at each mesh cell, but these systems are solved with the new time level pressures factored out on the right-hand sides to give equations of the form

$$vZ_{(i,j+\frac{1}{2})_f}^{n+1} = az_{(i,j+\frac{1}{2})_f} + bz_{(i,j+\frac{1}{2})_f} (p_{(i,j+1)}^{n+1} - p_{(i,j)}^{n+1}) \tag{16}$$

Equation (16) is the required relationship between new time-level pressures and velocities. The linear coefficients az and bz are held constant during the next step. An analogous procedure for the radial momentum equations yields a similar equation set for the radial velocities.

$$vR_{(i+\frac{1}{2},j)_f}^{n+1} = ar_{(i+\frac{1}{2},j)_f} + br_{(i+\frac{1}{2},j)_f} (p_{(i+1,j)}^{n+1} - p_{(i,j)}^{n+1}) \tag{17}$$

### B. Basic Step

All terms in the mass and energy equations (1), (2) and (5) are evaluated using control volumes at cell centers (i,j). Terms in these equations requiring further finite difference expansion follow.

$$\frac{\partial}{\partial t} (\alpha_f \rho_f) = \frac{\alpha_f^{n+1} \rho_f^{n+1} - AR_f^n}{\Delta t} , \quad (18)$$

where  $AR_f^n$  is calculated in the mass stabilizer step of the previous time step.

$$\frac{\partial}{\partial t} (\alpha_f \rho_f u_f) = \frac{\alpha_f^{n+1} \rho_f^{n+1} u_f^{n+1} - ARU_f^n}{\Delta t} , \quad (19)$$

where  $ARU_f^n$  is calculated in the energy stabilizer step of the previous time step.

The second term in equations (1), (2), and (5) has the form  $\nabla \cdot (Y\vec{V})$  and is evaluated as

$$\begin{aligned} \nabla \cdot (Y\vec{V}) &= \{EZ_{(i,j+\frac{1}{2})} [Y,VZ]_{(i,j+\frac{1}{2})} - EZ_{(i,j-\frac{1}{2})} [Y,VZ]_{(i,j-\frac{1}{2})} \\ &+ ER_{(i+\frac{1}{2},j)} [Y,VR]_{(i+\frac{1}{2},j)} - ER_{(i-\frac{1}{2},j)} [Y,VR]_{(i-\frac{1}{2},j)}\} / VOL_{(i,j)} . \end{aligned} \quad (20)$$

where EZ and ER represent axial and radial flow areas, respectively, and

$$\begin{aligned} [Y,VZ]_{(i,j+\frac{1}{2})} &= \frac{Y_{(i,j)}}{(1-\alpha_s)_{(i,j)}} VZ_{(i,j+\frac{1}{2})} \quad \text{if } VZ_{(i,j+\frac{1}{2})} \geq 0 \\ &= \frac{Y_{(i,j+1)}}{(1-\alpha_s)_{(i,j+1)}} VZ_{(i,j+\frac{1}{2})} \quad \text{if } VZ_{(i,j+\frac{1}{2})} < 0 . \end{aligned} \quad (21)$$

Similar upwind difference forms hold for the other terms in equation (20).

For the mass conservation equations (1) and (2),  $Y_{i,j}$  is given by  $a^{n+1} \rho^{n+1}$ . The neighboring cell  $Y$ 's are given by stabilized mass densities (AR), which are calculated in the mass stabilizer step of the previous time step. Similarly, for the energy conservation equations (5),  $Y_{i,j}$  is given by  $a^{n+1} \rho^{n+1} u^{n+1}$ , but the neighboring cell  $Y$ 's are given by stabilized energy densities (ARU), which are calculated in the energy stabilizer step of the previous time step. Using different time level values in the convection terms is nonconservative, but conservation is maintained by the mass and energy stabilizer steps. Using new time-level values of  $a\rho$  and  $a\rho u$  in the convection terms increases stability, while using old-time level values for the neighboring cells reduces the spatial coupling of the system of equations that must be solved (they are still coupled by pressures).

The work term in equation (5) is given by

$$p^{n+1} \left( \frac{a_f^{n+1} - a_f^n}{\Delta t} + \nabla \cdot (a_f^n \vec{V}_f^{n+1}) \right)$$

where the convection term is upwind-differenced as in equation (20).

Equations (16) and (17) are used to eliminate velocities in equations (1), (2), and (5). Equations (1), (2), (5), and (6) now constitute a set of 10 equations for each mesh cell. With material equations of state used to give internal energy and density in terms of pressure and temperature, these 10 equations are functions of the pressure field (cell and neighboring cell pressures), cell partial pressure of hydrogen, and cell values of volume fraction and temperatures for each of the four fluids.

These systems are solved by Newton iteration using the following procedure (which was developed for the two-fluid systems of TRAC/PF1). Variations in the 10 equations with respect to cell pressure are divided into those caused by density changes and those caused by velocity changes. The Jacobian matrix is partitioned so that variations with respect to cell variables are included on the left hand side of equation (22), while variations with respect to neighboring cell pressures and the terms for variation of velocity with respect to cell pressure are included on the right hand side.

$$\begin{aligned} \underline{A} \vec{\delta x} = & -\vec{B}_1 \delta p_{(i,j)} - \vec{B}_2 \delta p_{(i+1,j)} - \vec{B}_3 \delta p_{(i-1,j)} \\ & - \vec{B}_4 \delta p_{(i,j+1)} - \vec{B}_5 \delta p_{(i,j-1)} - \vec{S} \end{aligned} \quad (22)$$

where  $\underline{A}$  is the  $10 \times 10$  Jacobian matrix

$$\underline{A} = \begin{array}{cccccc} \frac{\partial M_1}{\partial p} & \frac{\partial M_1}{\partial a_1} & \dots & \frac{\partial M_1}{\partial a_4} & \frac{\partial M_1}{\partial T_1} & \dots & \frac{\partial M_1}{\partial T_4} & \frac{\partial M_1}{\partial p_h} \\ \vdots & & & & & & & \vdots \\ \frac{\partial M_5}{\partial p} & & & & & & & \vdots \\ \frac{\partial I_1}{\partial p} & & & & & & & \vdots \\ \vdots & & & & & & & \vdots \\ \frac{\partial I_4}{\partial p} & & & & & & & \vdots \\ \frac{\partial AL}{\partial p} & \dots & \dots & \dots & \dots & \dots & \dots & \frac{\partial AL}{\partial p_h} \end{array} \quad (23)$$

where the  $M_i$  represent equation (1) ( $i=1$  to 4) and equation (2) ( $i=5$ ). The  $E_i$  represent equation (5) ( $i=1$  to 4), AL represents equation (6), and

$$\vec{\delta x} = (\delta P, \delta a_1, \dots, \delta a_4, \delta T_1, \dots, \delta T_4, \delta P_h) . \quad (24)$$

$$\vec{B}_1 = \left( \frac{\partial M_1}{\partial P_{i,j}}, \dots, \frac{\partial M_5}{\partial P_{i,j}}, \frac{\partial E_1}{\partial P_{i,j}}, \dots, \frac{\partial E_4}{\partial P_{i,j}}, \frac{\partial AL}{\partial P_{i,j}} \right) . \quad (25)$$

$$\vec{S} = (M_1, \dots, M_5, \dots, E_1, \dots, E_5, \dots, AL) . \quad (26)$$

and  $\underline{A}$  and  $\vec{S}$  are evaluated using previous iterate values for the 10 independent variables, and  $\vec{S}$  represents the residuals of the 10 equations. Forms similar to equation (25) exist for the other  $\vec{B}_i$  in equation (22). Equation (22) is solved for  $\vec{\delta x}$  directly.

$$\begin{aligned} \vec{\delta x} = & -\underline{A}^{-1} \vec{B}_1 \delta P_{(i,j)} - \underline{A}^{-1} \vec{B}_2 \delta P_{(i+1,j)} - \underline{A}^{-1} \vec{B}_3 \delta P_{(i,j+1)} \\ & - \underline{A}^{-1} \vec{B}_4 \delta P_{(i,j-1)} - \underline{A}^{-1} \vec{S} . \end{aligned} \quad (27)$$

The first row of equation (27) is an implicit relationship between cell pressure variations and neighboring cell pressure variations. When the first rows of equations (27) are collected for all the mesh cells, an implicit system of equations for corrections to the pressure field results, which is solved iteratively. These pressure corrections are then substituted back into equation (27) for each mesh cell to give the rest of  $\vec{\delta x}$ . These corrections are then

applied to pressures, hydrogen partial pressures, and the four fluid volume fractions and temperatures. Equations (16) and (17) are used to update velocities. If the maximum pressure correction is greater than a specified convergence criterion, another Newton iteration is performed.

### C. Mass and Energy Stabilizers

Equations (1), (2) and (5) are converted to the following forms, respectively

$$\frac{AR_f^{n+1} - AR_f^n}{\Delta t} + \nabla \cdot (AR_f^{n+1} \vec{V}_f^{n+1}) - \sum_{k=1}^4 \Gamma_{kf} - \Gamma_f = 0, \quad (28)$$

$$\frac{AR_h^{n+1} - AR_h^n}{\Delta t} + \nabla \cdot (AR_h^{n+1} \vec{V}_h^{n+1}) - \Gamma_h = 0, \text{ and} \quad (29)$$

$$\begin{aligned} & \frac{ARU_f^{n+1} - ARU_f^n}{\Delta t} + \nabla \cdot (ARU_f^{n+1} \vec{V}_f^{n+1}) \\ & + p^{n+1} \left( \frac{\alpha_f^{n+1} - \alpha_f^n}{\Delta t} + \nabla \cdot (\alpha_f^n \vec{V}_f^{n+1}) \right) - \sum_{k=1}^4 \Gamma_{kf} h_{sf} - \sum_{k=1}^4 Q_{kf} - Q_f = 0, \end{aligned} \quad (30)$$

where all parameters are set using the new values determined in the basic step. These equations are solved for  $AR^{n+1}$  and  $ARU^{n+1}$  for each fluid and for hydrogen. These parameters provide stabilized mass and energy densities for the neighboring cell convective terms in the next time step.

#### D. Treatment of Low Volume Fractions

A lower limit is set on volume fractions that are calculated by the algorithm. This limit is provided as part of the code input, and is usually set to  $10^{-5}$ . If the volume fraction of a given fluid in a given cell, as determined by the mass stabilizer equations (27) and (28), is less than this lower limit, then the equation set is adjusted as though the fluid did not exist in that cell. This adjustment varies depending on the specific equation.

The spatially decoupled momentum equations (13) and (15) at a given cell interface are adjusted if the given fluid does not exist in both cells bordering the cell interface. This adjustment consists of fixing the linear coefficients to produce the required velocity. The momentum stabilizer equations (14) and the energy stabilizer equations (30) are not solved for a given fluid if that fluid does not exist anywhere in the vessel. The mass stabilizer equations (28) and (29) must be solved, because these equations determine whether a fluid has entered or left a given cell because of convection or source terms.

The most important adjustments are to equations (22). When a fluid is not present in a cell, the mass and energy conservation equations for that fluid can be removed from the equation set that make up equation (21), reducing the size of the system that must be solved. Thus the size of the matrix  $\underline{A}$  can range from  $10 \times 10$  (four fluids plus hydrogen) to  $2 \times 2$  (one fluid). The number of operations required to solve equation (22) directly is proportional to the dimension of  $\underline{A}$  cubed, so this procedure can result in a maximum reduction of a factor of 125 in the number of operations required. This procedure is effective in reducing overall computation time because most cells in a reactor vessel often contain only a single fluid during a typical accident sequence.

## 5. SUMMARY

An efficient algorithm for the mechanistic solution of in-vessel fluid dynamics and heat transfer during a core disruptive accident has been described. The algorithm allows discrete interpenetrating motion of four classes of materials. Structural materials can relocate to other regions of the vessel, displacing and interacting with other fluids (for example, by energetic fuel coolant interactions). This algorithm represents a significant extension of the well-proven SETS method. The new FLUIDS module of MELPROG has undergone testing in both stand-alone and coupled form against both experimental data and results of other codes. It will soon be used to give a fully integrated simulation of the important phenomena that occur during high-consequence PWR accident sequences.

NOMENCLATURE

$\alpha$	volume fraction
AR	macroscopic mass density (stabilized)
ARU	macroscopic energy density (stabilized)
$a_z, b_z$	coefficients in linearized axial momentum equations
$a_r, b_r$	coefficients in linearized radial momentum equations
CFZ, CWZ	inter-fluid and wall axial friction factors
CFR, CWR	inter-fluid and wall radial friction factors
FZ	axial flow area
FR	radial flow area
g	gravitational acceleration
h	enthalpy
i	axial node index
j	radial node index
P	pressure
Q	volumetric heat exchange rate
R	radial direction
t	time
T	temperature
u	internal energy
$\vec{V}$	two-component velocity vector
VZ	axial velocity
VR	radial velocity
VZP, VRP	axial and radial predictor velocities
VZS, VRS	axial and radial stabilizer velocities
VOL	cell geometric volume

$z$  axial direction  
 $\rho$  microscopic density  
 $\Gamma$  volumetric mass exchange rate

$\vec{r}$   
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